High-Performance Computing

Getting good performance from your application

Tuning techniques for serial programs on cache-based computer systems

Application Tuning

Overview

- Introduction
- Memory Hierarchy
- General Optimization Techniques
-
- Compilers
- Analysis Tools
- Tuning Guide

De-vectorization

- Cache space and bandwidth are scarce resources
- Compilers know this – but sometimes they have to store data that does not need to be stored.
- This impacts:
  - bandwidth
  - cache capacity
  - instruction scheduling

De-vectorization

- A typical problem with scratch data stored in vectors
- Difficult/impossible for the compiler to detect
- Depends on coding style

De-vectorization – Example

```
COMMON /SCRATCH/TMP(N)

DO I = 1, N
   TMP(I) = ...
        :
   ... = TMP(I)
END DO
        ⋮

DO I = 1, N
   TMP(I) = ..
        :
END DO
```

- *Because TMP() is global, the compiler has to store it in the first loop*
- *In the second loop, TMP() is overwritten, but the compiler will most likely not see this*
- *The programmer may know that TMP() is a scratch array only*

De-vectorization – Solutions

Array TMP needed later on:

```
REAL  T1,TMP(N)

DO I = 1, N
   T1 = ...
        :
   ... = T1
END DO
        ⋮

DO I = 1, N
   TMP(I) = ..
        :
END DO
```

Array TMP not needed later on:

```
REAL  T1

DO I = 1, N
   T1 = ...
        :
   ... = T1
END DO
        ⋮

DO I = 1, N
   T1 = ..
        :
END DO
```

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Stripmining

- *Large loops are difficult to optimize*
- *Especially the register allocation in the compiler has a hard time and can get confused*
- *Splitting the loop into smaller loops may improve performance*
- *However, this may cause scalars (local to the loop) to be replaced by vectors*
- *On very large loops this will increase memory usage notably*
- *Through stripmining memory usage can be kept under control*

```
DO I = 1, LONG
   X(I) = ...
   A    = ...
   Y(I) = A + ...
END DO
```

Split loop in two parts

```
DO I = 1, LONG
   X(I)  = ...
   VA(I) = ...
END DO

DO I = 1, LONG
   Y(I) = VA(I) + ...
END DO
```

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Stripmining – Code structure

```
DO i = is, ie
   ......
END DO
```

Stripmine this loop with length NS

```
DO i1 = is, ie, ns
   ivl = min(ie-i1+1,ns)
   DO i2 = 0, ivl-1
      i = i1+i2
      ........
   END DO
END DO
```

Split inner loop

```
DO i1 = is, ie, ns
   ivl = min(ie-i1+1,ns)
   DO i2 = 0, ivl-1
      i = i1+i2
      ........
   END DO
   DO i2 = 0, ivl-1
      i = i1+i2
      ........
   END DO
   DO i2 = 0, ivl-1
      i = i1+i2
      ........
   END DO
END DO
```

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Best practice

It is up to you to write code such that the compiler can find opportunities for optimization:

- Write efficient, but clear code
- Avoid very “fat” (bulky) loops
- Design your data structures carefully
- Minimize global data

Best practice

- Branches:
  - simplify where possible
  - try to split the branch part out of the loop
- Avoid function calls in loops (use inlining)
- Leave the low level details to the compiler

Summary

- Most tuning techniques presented here are generic, i.e. they (probably/hopefully) improve your code on all cache based systems.
- The *tuning parameters* may be different, though, since they depend on the underlying hardware:
  - cache sizes and levels
  - prefetch

  and your problem's *memory footprint*
- Use the *best* compiler available on your platform.

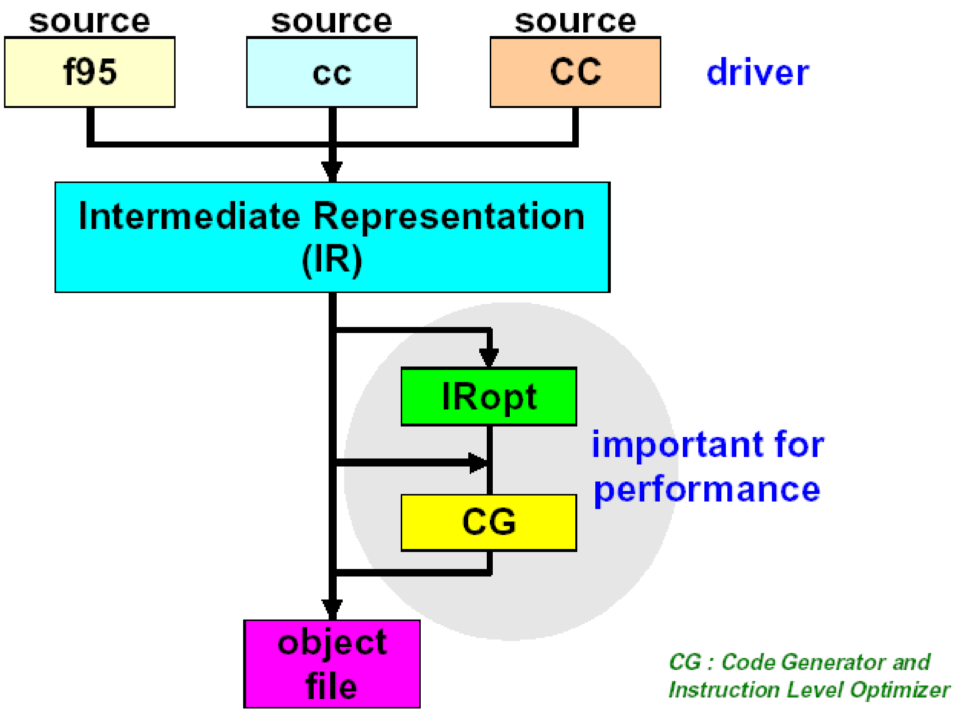
The Oracle Solaris Studio Compilers (a.k.a. Sun Studio) – an example how compilers work

Sun Studio: Overview

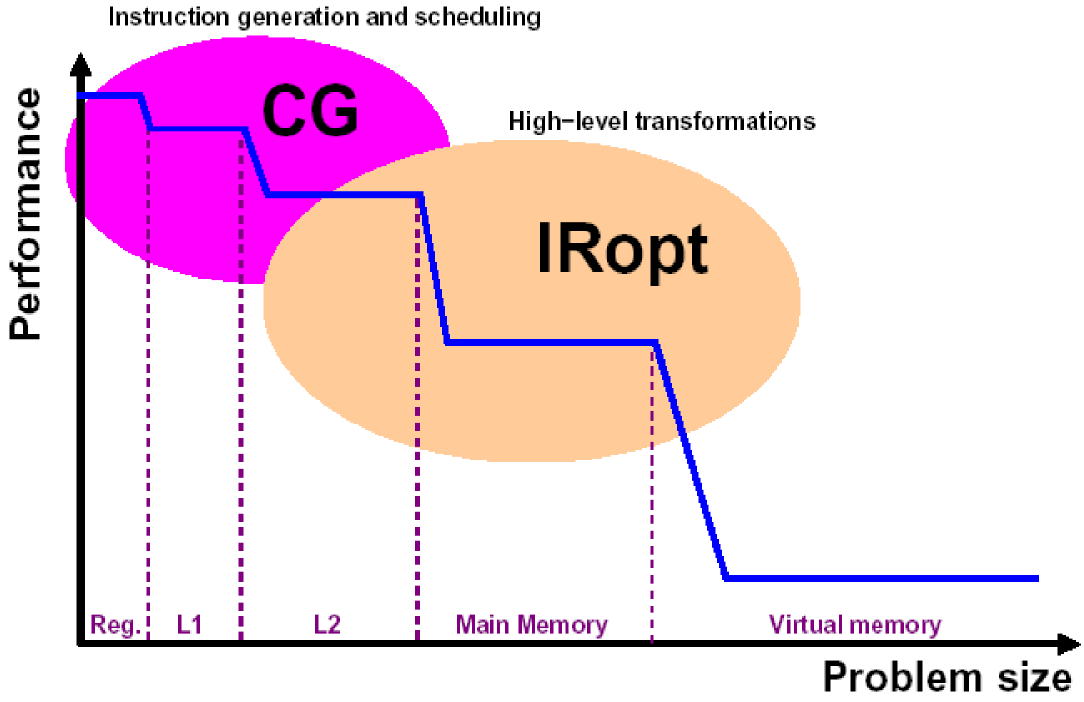
- ❑ Compiler Components
- ❑ Compiler Options
- ❑ Compiler Commentary
- ❑ Best practice

- ❑ Note: to use the Studio tools, you have to load the module first: '`module load studio`'

Sun Studio: Compiler Components



Sun Studio: Who does what?



Sun Studio: Minimal Compiler Options

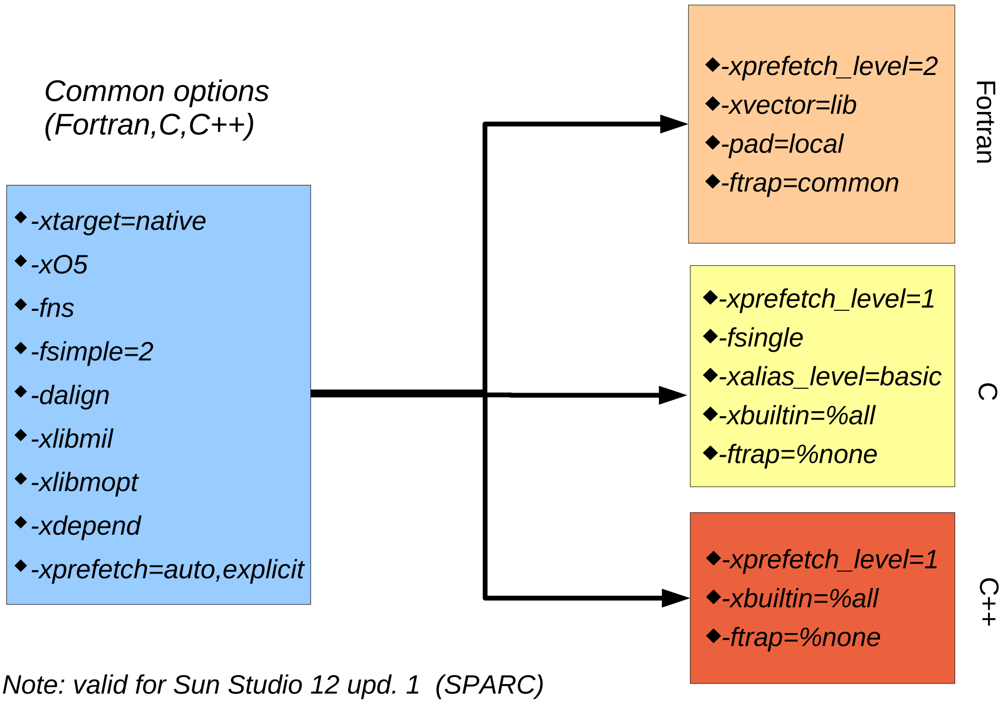
In general, one gets very good performance by just using 2 options for compiling and linking:

```
-g -fast
```

For specific x86_64-processors (cross-compiling):

AMD Opteron:	`-g -fast -xchip=opteron`
Intel Nehalem:	`-g -fast -xchip=nehalem`
Intel Westmere:	`-g -fast -xchip=westmere`
Intel Sandy Bridge:	`-g -fast -xchip=sandybrigde`
Intel Ivy Bridge:	`-g -fast -xchip=ivybridge`
Intel Haswell:	`-g -fast -xchip=haswell`
Intel Broadwell:	`-g -fast -xchip=broadwell`
Intel Skylake:	`-g -fast -xchip=skylake`

Sun Studio: The -fast macro



Note: valid for Sun Studio 12 upd. 1 (SPARC)

Sun Studio: Recommendations

- Use a Makefile and `make` for compiling/linking:

```
OPT    = -g -fast
ISA    =
CHIP   =
CFLAGS = $(OPT) $(ISA) $(CHIP)
```

- *Always start with `-fast` !*
- The compilers follow the 'rightmost option wins' rule, i.e. one can overrule options defined by the -fast macro.

Sun Studio: Recommendations

- `-fast` is a convenience macro that (in general) gives optimal performance with one single option
- `-fast` can change from one release to another!
- Use '`-fast -xdryrun`' to check what `-fast` expands to

What about other compilers? - I

- Other compilers have similar options, that combine many optimizations into a single option
- GCC: -O, -O3
- Intel: -O2 (default!), -O3, -fast
- look up in the manpages/documentation, what that corresponds to
- my experience: difficult to find out, not so easy to switch off 'unwanted options'

What about other compilers? - II

- GCC: show optimizer options
  - gcc -Q –help=optimizers -O3 ....
- shows a list of all known '-f...' options and their status
- switch extra options on/off, e.g. loop unrolling
  - -funroll-loops
  - -fno-unroll-loops

What about other compilers? - III

- Other compilers work in a similar way, but ...
- I've chosen Oracle Studio for various reasons:
  - my own experience
  - it is easy to use
  - it makes it easy to test effects of certain options
  - it is a nice tool for teaching
  - it makes it easier for you to understand certain aspects in this class
- Downside: It seems that Oracle has stopped further development of the product in 2017!

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Sun Studio: Optimization levels

- The level of optmization can be specified with the -xOn option
- Each level includes the lower levels
- Choices for n:
  - n = 1 – Basic block level optimizations
  - n = 2 – Some additional optimizations
  - n = 3 – Loop transformations and modulo scheduling
  - n = 4 – Intra-file inlining and pointer tracking
  - n = 5 – Aggressive optimizations

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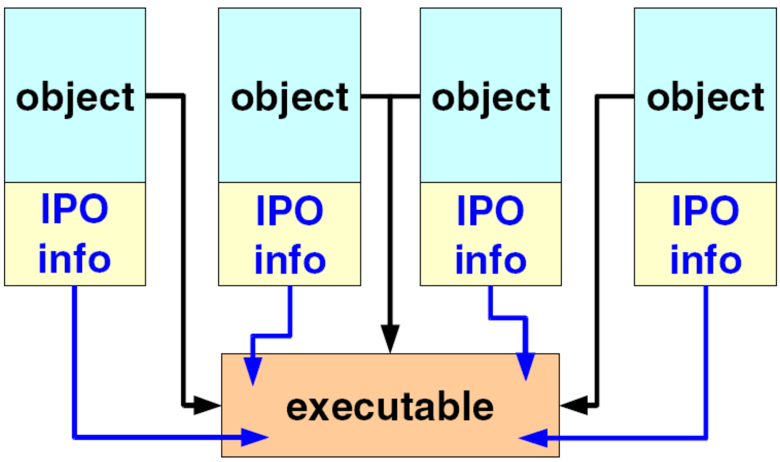
Inter Procedural Optimization

- With the -xipo option, the compiler stores additional information into the object files
- This information is used during the link phase to perform additional optimizations



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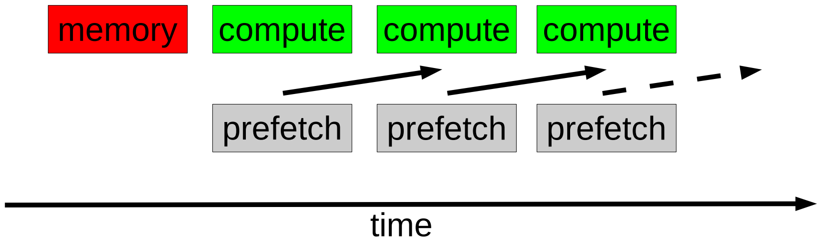
Prefetch: Hiding memory latency

- The number of clock cycles to access memory increases with the CPU clock speed.
- Prefetch is a way to overcome this:

  Fetch data ahead in time, anticipating future use.
- Special prefetch instructions must be available



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Prefetch Support

- Prefetch is a common feature in modern CPUs: both data and instruction prefetch.
- Implementation is system dependent!
- Examples of CPUs that support prefetch:
  - AMD Opteron
  - Intel (since Pentium 3, 4)
  - UltraSPARC IIIi, IIICu, IV, IV+
- Compilers have to support prefetch.
- There is hardware prefetch, too (Xeon, Opteron)

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Sun Studio: Prefetch options

- Automatic – done by the compiler:
  - -xprefetch=yes
  - Control level and type:
    - -xprefetch_level=n (n = 1, 2 or 3)
    - -xprefetch_auto_type=[no%]indirect_array_access
- Explicit – controlled by the user:
  - Either through functions calls (C/C++) or directives (Fortran).
  - Can be combined with automatic prefetch.
  - For more information see the compiler manual.

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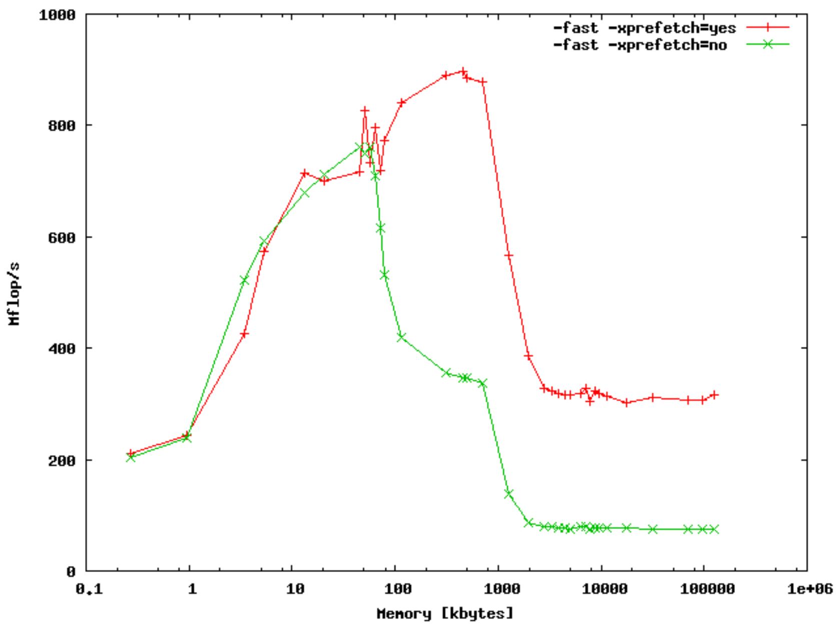
Prefetch: example

Example: Matrix times vector in C (row version)



US-IIIi @ 1062 MHz
L1 : 64 kB
L2 : 1 MB
Peak : 2.1 Gflop/s

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Pointer overlap – or "aliasing"

```
void vecadd(int n, double *a, double *b, double *c)
{
    for(int i = 0; i < n; i++)
        c[i] = a[i] + b[i];
}
```

```
vecadd(n, &a[0], &b[0], &a[1]);
```

```
void vecadd(n,  &a[0], &b[0], &a[1])
{
    for(int i = 0; i < n; i++)
        a[i+1] = a[i] + b[i];
}
```

Data dependency!

Sun Studio: C code and -xrestrict

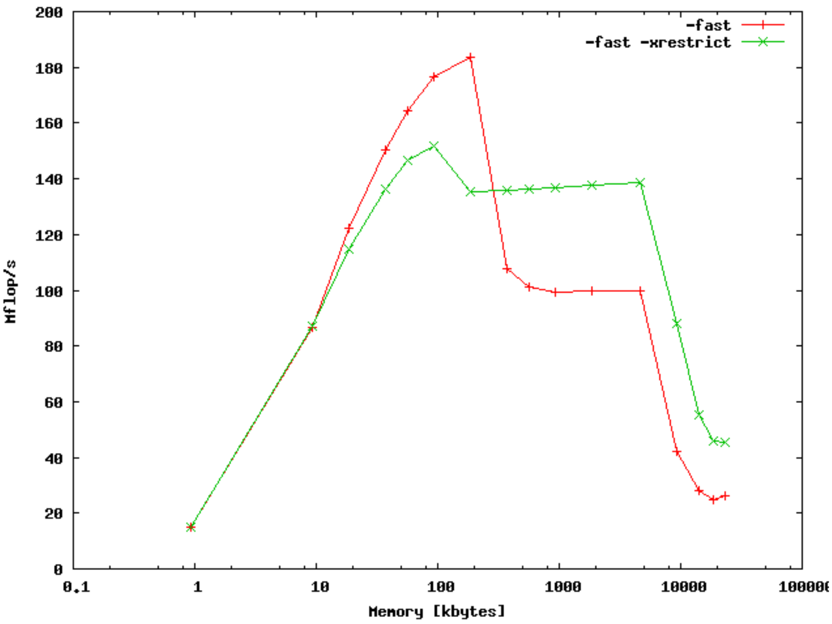
- Pointer aliasing problem: The C compiler <u>has to assume</u> that different pointers may overlap:
  - Correct – but non-optimal – code will be generated
  - Only the programmer might know, that there is no overlap.
- You can tell the compiler that there is no overlap, with the `–xrestrict` option.
- Note: It is then <u>your responsibility</u> that this assumption will not be violated!

Sun Studio: C code and -xrestrict

- Syntax: -xrestrict=n, where n is one of
  - %none : all pointers may overlap (default)
  - %all : no pointers overlap
  - f1[,f2] : a comma separated list of function names
- -xrestrict is the same as -xrestrict=%all
- Warning: Use -xrestrict only if you can make sure that the pointers <u>never</u> overlap!

Sun Studio: C code and -xrestrict

Vector addition example: non-overlapping vectors!



US-III @ 900 MHz
L1 : 64 kB
L2 : 8 MB
Peak : 1.8 Gflop/s
Sun Studio 10

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Pointer overlap – fix your code

- If you can assure that the pointers don't overlap, you can fix your code using the C99 'restrict' keyword:

```
void
vecadd(int n, double * restrict a,
       double * restrict b, double * restrict c)
{
    for(int i = 0; i < n; i++)
        c[i] = a[i] + b[i];
}
```

- Advantage: local change, no global assumption
- Needs a C99 compliant compiler to be portable!

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Sun Studio: Useful options – 1

- -flags : Lists all the available compiler flags on the screen (long list)
- -xhelp=readme : Displays the README file (release notes) on the screen
- -xdryrun : see what the compiler would do (macro expansion, no compilation!)
- -V : Shows the compiler version

```
% f90 -V
f90: Sun Fortran 95 8.4 SunOS_sparc 2009/06/03
Usage: f90 [ options ] files.  Use 'f90 -flags' for details
```

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Sun Studio: Useful options – 2

- -g : Generates debugging information and adds compiler commentary to the object file. Necessary if the performance analysis tools should be used.
- **Note**: -g can be used in connection with optimization!
- -xlibmopt : Optimized version of libm
- -xlibmil: Use fast assembly language inline templates for standard functions
- -xvector : vectorized intrinsics, e.g. sqrt()

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Sun Studio: Useful options – 3

- -xprefetch_level=<u>n</u> : Try different levels of prefetching (n = 1,2,3)
- -xrestrict : (C/C++) tell the compiler that your pointers do point to 'restricted areas' in memory, i.e. no overlap of arrays
- -stackvar : (Fortran) keep local data on stack
- -xlic_lib=sunperf : Link with the Sun Performance Library (LAPACK, BLAS, Sparse-BLAS (Netlib and NIST), FFT, Sparse Solvers)

Sun Studio: Useful options – 4

- Options that are useful under development – but should be avoided in production:
  - -C : array boundary checking (Fortran)
  - -pg/-p : Unix profilers – you don't really need them, use the Performance Analyzer instead.
  - -xcheck=... : implements runtime checks.
    - -xcheck=init_local : initialize local variables with a value that is likely to cause an arithmetic exception (Fortran)
    - -xcheck=stkovf : check for stack overflow.
  - -Xlist : check your Fortran code for inconsistencies (commented source in .lst file)

Sun Studio: Where to get it?

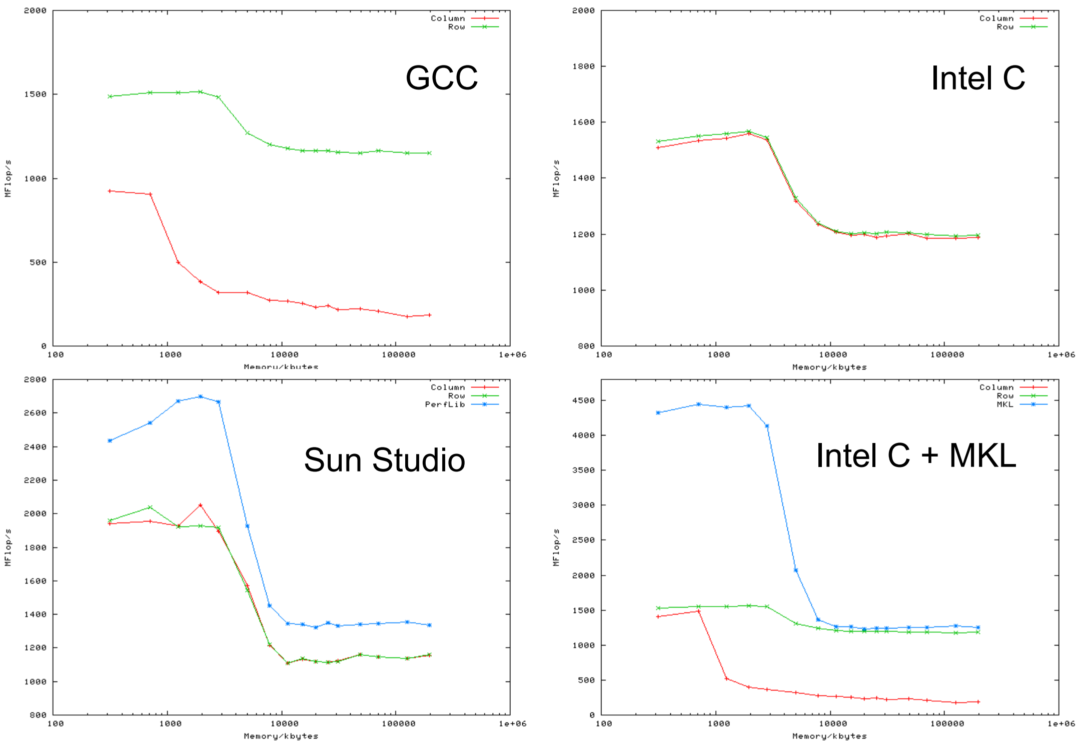
- Go to Oracle TechNetwork
- Download and install it – it is for free!

- Best practice: It is always good to have more than one compiler (or compiler version) at hand!
  - to test compatibility / portability
  - to exclude compiler bugs

Matrix times vector

- 2 code versions: Column and Row
- 3 compilers under Linux:
  - GCC
  - Intel C
  - Sun Studio C
- 2 libraries:
  - Intel MKL
  - Sun Performance Library
  - Note: this is a quick comparison! (June 2008)

Matrix times vector



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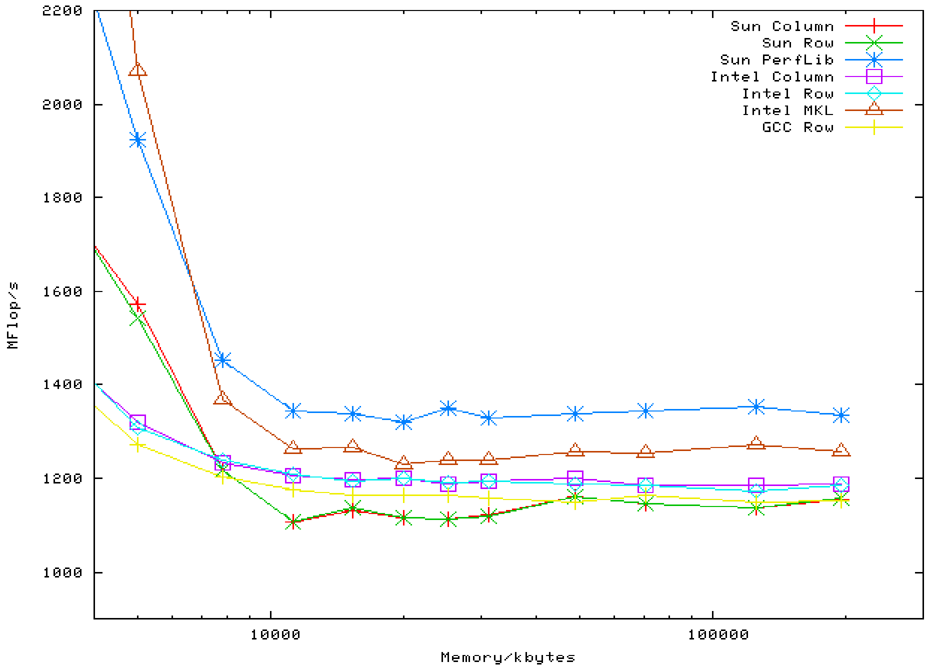
Matrix times vector

Comparison for large data sets:



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Ease of use – vendor library

- Intel/GCC with Intel MKL:
  - several compiler options
  - several linker options
  - depends on platform: IA32 or EMT64
  - set up of run-time environment
  - different downloads, installations and licenses
- Sun Studio:
  - one linker option: -xlic_lib=sunperf
  - no need to set up run-time environment
  - one download, installation – and no license

Compiler commentary

Sun Studio: Compiler Commentary

How do I know what the compiler did with my code?

- Compile with -g (C++: -g0) and use the er_src command on the object files:
  - This generates a code listing with comments from the compiler (also used in the Performance Analyzer GUI).
- Command: `er_src -src foo.c foo.o`
- Note: the examples on the next slides are from the Solaris SPARC version of Sun Studio – the x64 versions can differ

Application Tuning

Sun Studio: Compiler Commentary

```
// ex.c
#define A(i,j) a[(i)*n + (j)]
#define B(i,j) b[(i)*n + (j)]
#define C(i,j) c[(i)*n + (j)]

void
mysub(int m, int n, double *a, double *b,
      double *c) {

    int i, j;

    for(j = 0; j < n; j++)
      for(i = 0; i < m; i++)
        C(i,j) = A(i,j) + B(i,j);
}
```

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Sun Studio: Compiler Commentary

```
% cc -g -fast -c ex.c
% er_src -src ex.c ex.o
```

UltraSPARC

```
     5. void
     6. mysub(int m, int n, double *a,
               double *b, double *c){
        <Function: mysub>
     7.
     8.     int i, j;
     9.

   Source loop below has tag L1
    10.     for(j = 0; j < n; j++)

   Source loop below has tag L2
   L2 scheduled with steady-state cycle count = 5
   L2 unrolled 2 times
   L2 has 2 loads, 1 stores, 6 prefetches, 1 FPadds, 0
FPmuls, and 0 FPdivs per iteration

    11.         for(i = 0; i < m; i++)
    12.             C(i,j) = A(i,j) + B(i,j);
    13. }
```

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Sun Studio: Compiler Commentary

```
% cc -g -fast -xrestrict -c ex.c
% er_src -src ex.c ex.o
```

UltraSPARC

```
     5. void
     6. mysub(int m, int n, double *a,
              double *b, double *c){
        <Function: mysub>
     7.
     8.     int i, j;
     9.
   Source loop below has tag L1
   L1 interchanged with L2
   L1 scheduled with steady-state cycle count = 2
   L1 unrolled 4 times
   L1 has 2 loads, 1 stores, 3 prefetches, 1 FPadds, 0
FPmuls, and 0 FPdivs per iteration

    10.     for(j = 0; j < n; j++)
   Source loop below has tag L2
   L2 interchanged with L1
    11.        for(i = 0; i < m; i++)
    12.            C(i,j) = A(i,j) + B(i,j);
    13. }
```


Sun Studio: Compiler Commentary

```
% cc -g -fast -xrestrict -c ex.c
% er_src -src ex.c ex.o
```

x86_64

```
     5. void
     6. mysub(int m, int n, double *a,
              double *b, double *c){
        <Function: mysub>
     7.
     8.     int i, j;
     9.
   Source loop below has tag L1
   L1 interchanged with L2
   L1 cloned for microvectorizing-epilog.  Clone is L6
   L1 is micro-vectorized

    10.     for(j = 0; j < n; j++)
   Source loop below has tag L2
   L2 interchanged with L1
    11.        for(i = 0; i < m; i++)
    12.            C(i,j) = A(i,j) + B(i,j);
    13. }
```

Application Tuning

Sun Studio: Compiler Commentary

```
% cc -g -fast -xrestrict -xvector=no%simd -c ex.c
% er_src -src ex.c ex.o
```

x86_64

```
     5. void
     6. mysub(int m, int n, double *a,
              double *b, double *c){
        <Function: mysub>
     7.
     8.     int i, j;
     9.

   Source loop below has tag L1
   L1 interchanged with L2
    10.     for(j = 0; j < n; j++)

   Source loop below has tag L2
   L2 interchanged with L1
    11.       for(i = 0; i < m; i++)
    12.           C(i,j) = A(i,j) + B(i,j);
    13. }
```

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Application Tuning

Sun Studio: Compiler Commentary

```
% cc -g -fast -xrestrict -c ex2.c
% er_src -src ex2.c ex2.o
```

```
     7. void
     8. mysub(int m, int n, double *a,
              double *b, double *c){
        <Function: mysub>
     9.
    10.     int i, j;
    11.
   Source loop below has tag L1
    12.     for(j = 0; j < n; j++)
   Source loop below has tag L2
    13.       for(i = 0; i < m; i++) {
    14.           C(i,j) = A(i,j) + B(i,j);

   Function mean not inlined because the compiler has
not seen the body of the routine
    15.           mean(C(i,j));
    16.       }
    17. }
```

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Compiler Commentary – I

Why is this useful?

- Compilers are no longer a black box!
- What the compiler has done – or hasn't done/couldn't do – to the code is made visible to the programmer.
- Useful information is provided, so a programmer can take action, e.g.
  - code changes
  - different set of compiler options

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Compiler Commentary – II

More reasons, why it is really useful:

- annotations are where they belong: in the code – and not on the screen during compilation (or in a log file)
- review at any time – even a long time after the code has been compiled
- visible in the analyzer output as well, together with runtime profile

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Other tricks

Reconstruct the compiler options from the object files and/or executable:

- dwarfdump file.o (C/C++/Fortran)
- dumpstabs file.o (Fortran, before Studio 12u1)

- and look for
  - command_line (dwarfdump) or
  - CMDLINE (dumpstabs) in the output.
- Very useful to check what has been done.
- Note: dwarfdump works for GCC .o files, too

Analysis tools

Analysis tools

- analysis tools are useful to detect bottlenecks in codes
- modern analysis tools (unlike “old” profilers) work even on 'non-instrumented' code: no need to recompile (in principle)
- runtime profiles down to the source level (profilers usually work on function/subroutine level)

Analysis tools

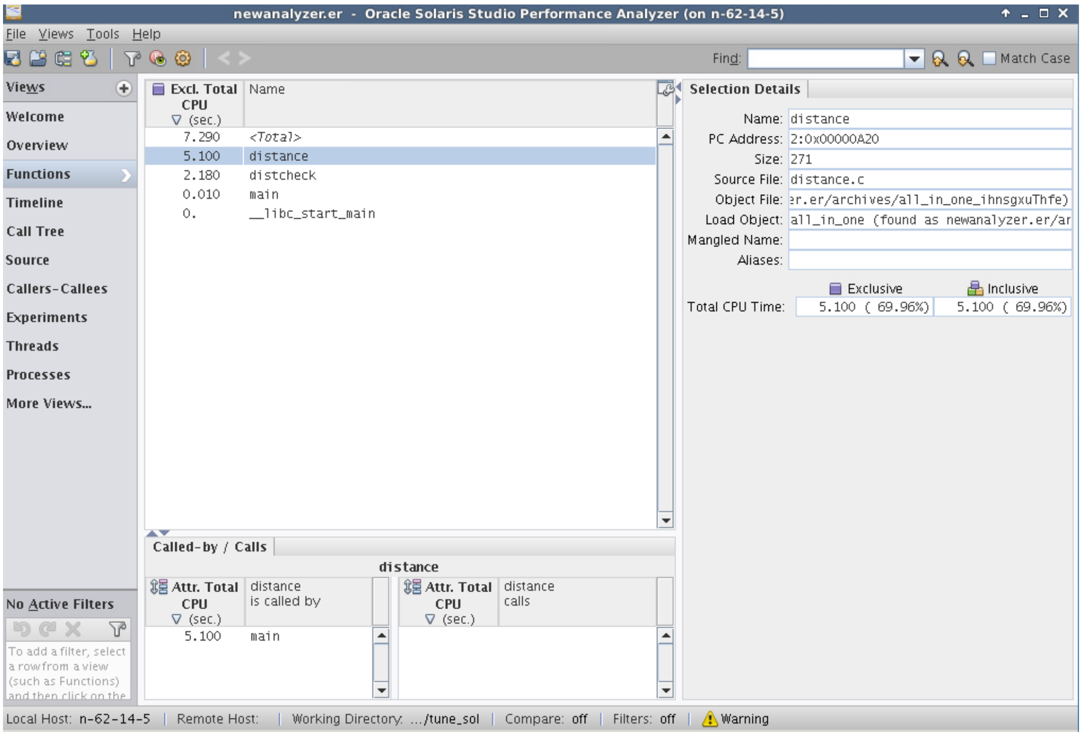
- Oracle: Solaris Studio Performance Analyzer
  - Linux (x64)
- Intel: Vtune Performance Analyzer (Windows/Linux)
- Mac OS X: Instruments (part of Xcode)
- 'perf' command line tool (Linux)
- Google Performance Tools (Linux/Windows):
  - collection of runtime libraries and command line tools

Sun Studio: Performance Analyzer

- Sun Studio provides a powerful toolset for runtime analysis
- Both GUI and command line tools
  - analyzer – GUI for collecting and analyzing performance data
  - collect – Command to collect performance data
  - er_print – Command to analyze performance data in ASCII format (good for scripting)

Sun Studio: Performance Analyzer

Application Tuning



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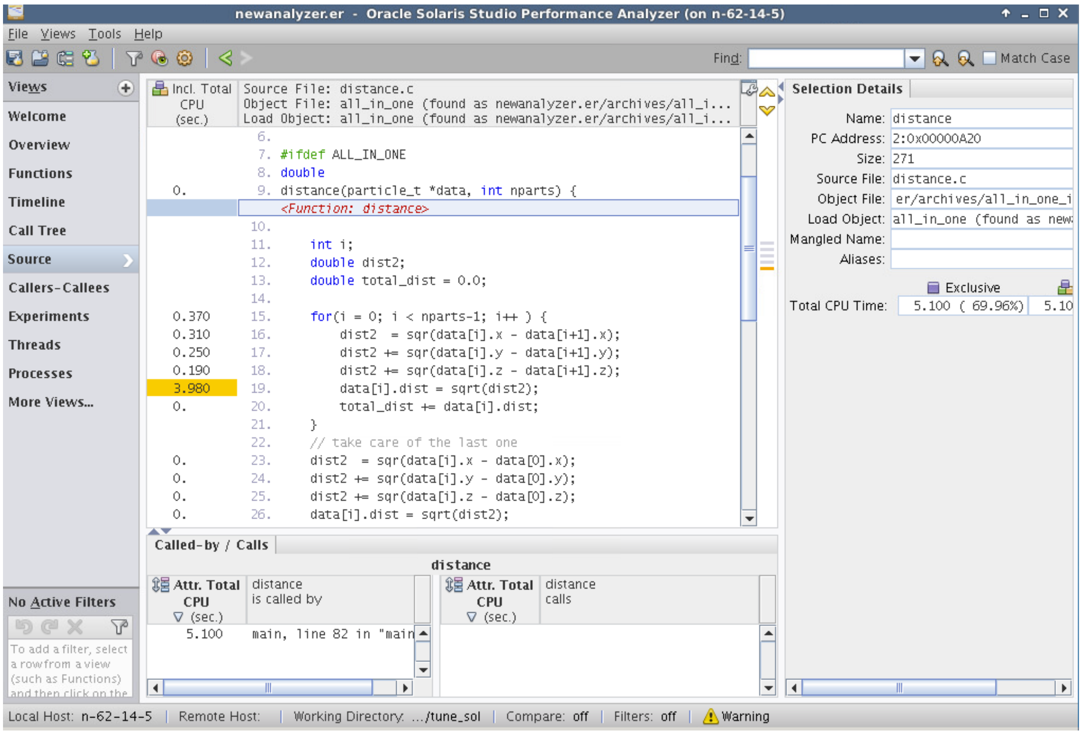
Sun Studio: Performance Analyzer



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Hardware Performance Counters

- Almost all modern CPUs have built-in hardware performance counters:
  - How many instructions were executed?
  - How many clock cycles were used?
  - How many L1 data cache misses occured?
- The supported counters are usually listed in the architecture reference manuals.
- Be aware: The counter names are not for beginners!

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Using the Performance Counters

- Native OS tools, e.g. Linux:
  - perf – Performance monitoring tool
  - requires newer Linux kernel (> 2.6.31)
  - examples:

```
% perf stat -e <event_name> -- command
% perf stat -e <event_name> -p PID

% perf record -e <event_name> -- command
% perf report
```

  - 'perf top' - requires root priviliges

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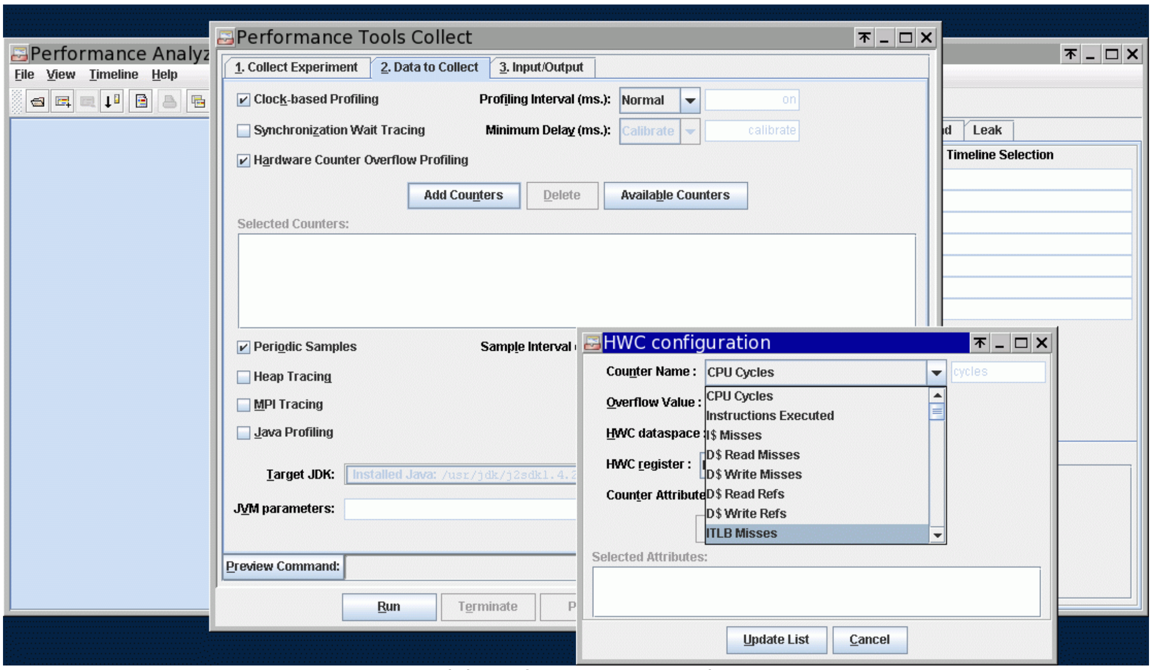
Using the Performance Counters

- Available performance counters:
  - system and CPU dependent
  - get a list:
  - `% perf list`
  - `% collect` (no argument)
  - example: no. of available performance counters on
    - US-IV: 70
    - US-IV+: 101
    - AMD Opteron: 169
    - Xeon E5-... v3: 269

Using the Performance Counters

Activating performance counters in analyzer:



Sun Studio: Performance Analyzer

Analyzer demo

Application Tuning

Tuning Guide – compact version

- Make a 'baseline' version (with different data sets/memory requirements)
- Try to find the best compiler options
  - with or w/o prefetching
  - ...
- Use analysis tools to locate the 'hot spots'
- Introduce code changes
- Repeat the last two steps until you are satisfied

Application Tuning

End of lecture 2